How to analyze LAT observations of AGN

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1. Introduction

This document illustrates the basic procedure of extracting science products (images, spectra, light curves) from a LAT observation of an AGN. We will concentrate on blazars, i.e., bright point-like sources.

Two study cases are discussed. First, an isolated AGN, i.e., a source with no point sources within 20–30 degrees. Second, an AGN in a crowded field. The basic difference in the analysis is that, because of the large PSF of the LAT, especially at lower energies, in the second case the analysis needs to take into account ALL sources contributing to the flux in the region of interest. This is accomplished by simultaneous spatial-spectral modeling of the sources with maximum likelihood.

A collection of light curves and SEDs for all the DC2 blazars can be found at `http://www.asdc.asi.it/glast/dc2cat/`. Note, however, that the light curves at this site were extracted without making any attempt at modeling nearby contaminating sources (see below). However, for bright sources the curves allow a qualitative inspection of the variability trend.

Additional information on the GLAST tools can be found at

`http://glast.gsfc.nasa.gov/ssc/dev/Analysis_Tools_Documentation/`.

2. Getting started

You will need to following packages/interfaces installed on your local computer:

- The SAE tools. For the purposes of this document we will use the interactive versions of the software version v7r5.

- A tool to plot images, e.g., ds9
- The FTOOLS package in order to manipulate files and perform some analysis (e.g., timing)
- Your favored file editor

In addition, you will need to download some files necessary for the analysis. Go to http://glast.gsfc.nasa.gov/ssc/dev/databases/DC2/ and download to your local server the following files:

- LAT pointing history and Live time files (`DC2_FT2_v2.fits`): this is your FT2 file containing attitude information
- The LAT source Catalog (the ds9 Region File, `LATSourceCatalog_v2r1.reg`), containing the list and positions of all simulated DC2 sources
- Galactic diffuse emission model (`GP_gamma.fits`), self explanatory

In addition, the GSSC has pre-calculated livetimecube files to expedite the LAT spectral analysis. Click on the Livetime Cubes link. It will take you to a page with the Livetimecube files for the total DC2 exposure of 55 days (`expCube_full.fits`) and for each single day. Since for this exercise we will consider the entire exposure, download `expCube_full.fits` to your local disk.

3. Case study 1: Isolated bright AGN

3.1. Summary

The case of an isolated AGN is the simplest, and will be used to illustrate the use of the basic tools. The blazar chosen for this demonstration is PKS 0208–51. We will learn how to:

- Retrieve and inspect LAT data of interest
- Extract the LAT spectrum of the AGN over the total exposure
- Extract the AGN light curve
- Perform time-resolved spectroscopy

3.2. Retrieving and inspecting the data

For this exercise we will use the Data Challenge (DC) 2 data, which are a simulation of 55 days of LAT observations of the sky. To access the data we will use the database interface at

`http://glast.gsfc.nasa.gov/cgi-bin/ssc/LAT/DC2DataQuery.cgi`

under the link `LAT Photon data - link to Photon database search engine.`

Figure 1 shows the main page of the retrieval database. As shown, we have the options of searching the database for position/object name or by date. Let's use the first option, and do a search by coordinates. For PKS 0208, RA(J2000)=02h10m46.2s, DEC(J2000)=–51d01m02s.

- Write RA and DEC in the blank space "Object name or coordinates";
- Go to the pull-down menu "Coordinate Systems" and select the equinox 2000;
- In "Area to Search" select the radius of extraction. Here, we'll use the default, 15 degrees. An extraction region radius of 15–20 deg is recommended for most likelihood

analyses. This is because due to the large PSF of the LAT, contamination from nearby sources is present for the source of interest which need to be taken into account by the maximum likelihood;

- Click on Select Data and follow download instructions. Let's rename the event file `pks0208-events.fits`.

Once the event file is downloaded, you can plot it using `ds9`, `fv`, or other image displayer of choice. Figure 2 shows the plot of `pks0208-events.fits` with ds9:

```
[rms@kea] ds9 -bin factor 0.1 0.1 "pks0208-events.fits[bin=RA,DEC]" &
```

By adjusting the `factor` you can plot the image with a heavier (> 0.1) or lighter (< 0.1) binning. To zoom in or out of the image, use the button `zoom` in the ds9 window. Select your favored color scale by clicking on `scale` and choosing an option - either `a, b, bb` will do. Change the intensity by right-clicking the mouse and moving it around the image.

For `pks0208-events.fits` the blazar is apparent at the center of the field. You can read its center coordinates in pixels or physical (degrees) in the `Image` space on the top-left of the ds9 window. The numerical content of the pixel (number of counts) is displayed in the `Value` space on top-left. In our case, X=253, Y=150.5, and Value=59 at the centroid of the source.

Left-clicking the mouse in the image will display a green circle. To get rid of it, just click anywhere inside the circle and then hit the Delete button on your keyboard.

3.2.1. Spectral Analysis

We will now extract the LAT photons in a region around PKS 0208 and analyze it with the maximum likelihood, `gtlikelihood`, to find the best representation of the spectrum and its parameters. Since we are dealing with a bright source, we will perform an unbinned analysis. This involves several steps:

1) select the optimal energy range (`gtselect`);

2) create the livetimecube (`gtlivetimecube`);

3) create an exposure map (`gtexpmap`);

4) create the source model in an XML file (`ModelEditor`);

5) create the diffuse emission responses (`gtdiffresp`);

6) run max likelihood (`gtlikelihood`).

In particular, `gtexpmap` requires in input the livetimecube file appropriate for the period of observation. In our case, since we are analyzing data collected over the entire 55 days of the survey, this file is `expCube_full.fits`.

1) Selecting the energy range: It is a good idea to restrict our analysis to data in the energy range 30 MeV – 300 GeV, where the LAT calibrations are best known. To select data in a given energy range we use `gtselect`. To start the tool, just type on the command line

```
[rms@kea] gtselect
```

The program will ask several questions:

```
[rms@kea] gtselect
Input FT1 file [] :  pks0208-events.fits
```

```
Output FT1 file [] : pks0208-events-encut.fits
RA for new search center (degrees) <0 - 360> [] : 32.6925
Dec for new search center (degrees) <-90 - 90> [] : -51.0172
radius of new search region (degrees) <0 - 180> [] : 15
start time (MET in s) [0] :
end time (MET in s) [0] :
lower energy limit (MeV) [] : 30
upper energy limit (MeV) [] : 300000
Event classes (-1=all, 0=FrontA, 1=BackA, 2=FrontB, 3=BackB, 4=class
A) <-1 - 4> [-1] :
Done.
```

Notes:

- The coordinates must be entered in degrees.
- For the "Radius of new search region" we specified 15 degrees, the extraction region we used for the LAT data selection in § 3.2. This Region Of Interest (ROI) must be entirely contained in the extraction region of the event file, or supersede the latter; there can not be partial overlap between the two.
- The Event classes refer to the various categories into which the reconstructed events are grouped (see below). Here we use the default, -1=all.

The Event classes are the result of the analysis of the DC2 data. The choice of a specific Event class for the analysis depends on the science goals and on the brightness of the source. For example, the Event class `0=FrontA`, which contains the photons interacting in the front section of the LAT, can be used to minimize the width of the PSF; however, the effective area decreases as well. This choice is thus optimal for timing and/or spectral analysis of a bright, isolated source. Event class `-1=all` includes all the photons interacting in various parts of the LAT, clearly maximizing the sensitivity at the expense of the resolution.

2) Creating the livetime cube: The livetimecube file contains the amount of livetime spent by the LAT observing a given region of the sky at a specified inclination angle between the LAT normal and the sky. As this quantity is independent from the source, a set of precomputed livetimecube files are available from the main GSSC download page `http://glast.gsfc.nasa.gov/ssc/dev/databases/DC2/`.

Alternatively, the livetimecube can be created using `gtlivetimecube`. Warning: the execution time of this tool can be very long.

```
[rms@kea] gtlivetimecube
Event data file [test_events_0000.fits] : pks0208-events-encut.fits
Spacecraft data file [test_scData_0000.fits] : DC2_FT2.fits
Output file [expCube.fits] : pks0208-expcube.fits
Step size in cos(theta) <0. - 1.> [0.025] :
Pixel size (degrees) [1] :
Working on file DC2_FT2.fits
.....................!
```

Obviously, the smaller the step size for the angle, the longer the execution time.

3) Creating an exposure map: The exposure map is needed in order to correct the counts map for disuniformities in the exposure time due to the variation of the detector efficiency with off-axis position. An exposure map is created using the tool `gtexpmap`:

```
[rms@kea] gtexpmap
The exposure maps generated by this tool are meant
to be used for *unbinned* likelihood analysis only.
Do not use them for binned analyses.
Event data file [pks0208-events-encut.fits] : pks0208-events-encut.fits
Spacecraft data file [DC2_FT2.fits] : ../DC2_FT2.fits
Exposure hypercube file [expCube_full.fits] : pks0208-expcube.fits
output file name [pks0208-expmap.fits] :
Radius of the source region (in degrees) [24] :
Number of longitude points <2 - 1000> [120] :
Number of latitude points <2 - 1000> [120] :
Number of energies <2 - 100> [20] :
Computing the ExposureMap using pks0208-expcube.fits
....................!
```

The "source region" is the region used for the maximum likelihood analysis; the Region Of Interest (ROI) refers to the region used to extract the data from the LAT field of view; in our case the ROI had radius 15°. Note that here we gave a larger radius for the source region than in `gtselect`. This is because, due to the large PSF size, contributions from nearby sources might be included in the source region; the latter thus needs to be large enough to contain the PSF of these nearby sources, which need to be taken into account to model the data. Giving the same radius as in `gtselect` will return the following Warning:

```
The radius of the source region, 14, should be significantly larger
(say by 10 deg) than the ROI radius of 14
```

Again, the exposure map can be plotted with ds9 for inspection:

```
[rms@kea] ds9 -bin factor 0.1 0.1 "pks0208-expmap.fits[bin=RA,DEC]" &
```

4) Setting up the model: The maximum likelihood performs a simultaneous spatial AND spectral modeling of the LAT field of view. Thus, the input model for `gtlikelihood` will need to specify:

- A spatial model for the point source
- A spectral model (power law, double power law, etc.)
- The diffuse extragalactic background spatial and spectral models
- The Galactic background spatial and spectral models.

To set up the model for the LAT data of PKS 0208, open ModelEditor by typing

```
[rms@kea] ModelEditor &
```

A pop-up window will appear on the screen, named "Source Model Editor" (Figure 3). This window allows us to add sources, select the spectral and spatial models, and enter our initial guesses for the parameter values.

Point Source: To add the point source, go to the pull-down menu under Edit and select "Add point source". Now click on the field "point source 0" on the top-right and write in the name of the source, for record keeping: PKS 0208 (see Figure 4).

Let's set up the the spectral model. Go to the "Spectrum" sub-window and click on the "PowerLaw" button next to it; a list of models will appear. Select PowerLaw, which should also be the default model. By double left-clicking on the Parameter name, we can edit the parameters: Value, Scale, Min, Max, and Free (Figure 5).

- Value: the numerical value of the parameter
- Scale: the order of magnitude of the value, typically an exponential number
- Min and Max: the minimum and maximum values the parameter can assume
- Free: a tag that indicates whether the parameter is fixed (0) or free to vary (1)

The actual value of the parameter used in the calculation is the product of the value and the scale. The units for the Prefactor (the normalization) are ph cm^{-2} s^{-1} MeV^{-1}.

After entering the initial guesses for the parameter, click OK to exit the menu.

Next, we set up the spatial model. Go to the next sub-window, click on the field next to it; a list of spatial models will appear. For a point source like PKS 0208, select "SkyDirFunction" which should also be the default choice. Double left-click on the parameters "DEC" and "RA" and write the corrdinates of our sources, in degrees (Figure 6). Since we know the coordinates of our source, we want to set the `Free` tag to 0 (fixed parameter). Click OK after entering the values.

Before we move to the next component of the model, we need to save the information for the point source. To do this, click on "Set components" (top-right) before proceeding.

Extragalactic Diffuse: We now need to add the background, starting with the extragalactic component. Go back to the Model Editor main window and under the Edit menu select "Add extragalactic diffuse". The spectral and spatial models (PowerLaw and Constant) should be automatically set up in the respective sub-windows (Figure 7). Fix all parameters (`Free=0`) except the PreFactor of the Spectral model.

Again, click "Set components" before proceeding.

Galactic Diffuse: To add the Galactic component, we proceed in a similar manner as for the Extragalactic one. Under the Edit menu, select "Add GalProp Diffuse". The default spectral model should be "ConstantValue", while the default spatial model should be "MapCubeFunction" in the corresponding windows.

Don't forget to "Set components" before you move on.

The model for the maximum likelihood is now done. This model needs to be saved in an ASCII file which will be used as input for `gtlikelihood`. To save into the file, go to "File" in the Source Model Editor window and select "Save as..."; let's call it `pks0208-model.xml`. This file can be edited using your favored editor, and the values of the parameters directly changed if needed. Figure 8 shows what the file looks like.

You can also read the model back into ModelEditor for modifications. Click under File in the ModelEditor window and select Import; it will prompt you for the name of the model.

5) Creating the diffuse spectral response: We are now ready to create the diffuse response using `gtdiffresp`. This tool will not create a new file, but rather it will add columns to the FT1 file given as input. Warning: this tool usually takes some time to run.

```
[rms@kea] gtdiffresp
Event data file [] : pks0208-events-encut.fits
Spacecraft data file [] : DC2_FT2.fits
Source model file [] : pks0208-model.xml
Response functions to use <DC2|DC1A|G25> [DC2] :
Computing exposure at (308.983, 32.6925).....................!
adding source Extragalactic Diffuse
adding source GalProp Diffuse
adding source point source 0
```

```
Working on...
pks0208-events-encut.fits......
```

Note that if no diffuse response is created explicitly `gtlikelihood` will compute one automatically. Precomputing the diffuse response becomes useful when one has to run `gtlikelihood` multiple times on the same file, because it reduces the execution time of the likelihood.

6) Running the Maximum likelihood: Because of the large PSF of the LAT, analysis of a source in a specified region of interest will contain contributions from nearby sources, and obviously from the background. The maximum likelihood searches for the best set of spatial and spectral parameters that maximize the "likelihood" quantity, i.e., that provide the largest probability to be an adequate representation of the LAT data in the region of interest.

There are two types of likelihood analyses: an **unbinned** analysis, where the likelihood is calculated using all the photons in the event file individually; and a **binned** one, where the data are binned together and which thus runs faster.

We are now ready to model the LAT data of PKS 0208 with the maximum likelihood. As mentioned, for this exercise we use the unbinned analysis and the interactive version of the tool.

```
[rms@kea] gtlikelihood


Statistic to use <BINNED|UNBINNED> [UNBINNED] :
Spacecraft file [] : DC2_FT2.fits
Event file [] : pks0208-events-encut.fits
Unbinned exposure map [] : pks0208-expmap.fits
```

```
Exposure hypercube file [] : expCube_full.fits
Source model file [] : pks0208-model.xml
Response functions to use <DC2|DC1A|G25> [DC2] :
Optimizer <LBFGS|MINUIT|DRMNGB> [DRMNGB] :
```

There are three algorithms that search for the paramater space corresponding to the maximum of the likelihood: LBFGS, DRMNGB, and MINUIT. The first two have faster execution times but are less accurate than the third algorithm, MINUIT. It is thus recommended that, after a first run using DRMNGB to find the parameter space, the tool be run again using the found parameters but with the MINUIT option.

Here we will first use DRMNGB, whose output is displayed on the screen and looks like this:

```
[.....]

Extragalactic Diffuse:
Prefactor: 2.48804 +/- 0.0269072
Index: -2.1
Scale: 100
Npred: 14454.2

GalProp Diffuse:
Value: 1
Npred: 4638.48

point source 0:
```

```
Prefactor: 31.4338 +/- 0.587055

Index: -2.17518 +/- 0.0110685

Scale: 100

Npred: 8726.76

ROI distance: 0.0311557

TS value: 24331.9

WARNING: Fit may be bad in range [30, 9176.18] (MeV)

WARNING: Fit may be bad in range [22133.6, 34375.4] (MeV)

WARNING: Fit may be bad in range [82916.1, 128776] (MeV)


Total number of observed counts: 27764

Total number of model events: 27819.4


-log(Likelihood): 297351.0757


Elapsed CPU time: 90.44
```

The best-fit values of the parameters and their 1σ uncertainty are provided. In addition, the program provides the number Npred of predicted events attributable to a source given the model parameters; the total number of observed and model counts for the region of interest; and the TS statistic. The latter is defined as TS=-2(log(Like) - log(Like0),) where Like0 is the maximum likelihood in the hypothesis that the source in question is not included in the model; the square root of TS is roughly the n-sigma significance of the source.

This information is also written in an ASCII file named by default `results.dat`. It is possible to redirect the results in a file of your chosen name by using the following command line:

```
gtlikelihood flux_style_model_file=my_model.xml
```

While it is not possible to derive a “goodness” of fit from the maximum likelihood method, it is useful to note that the ratio of the likelihood values for two different models is distributed as χ^2. Qualitatively, the model with the larger value of the likelihood (i.e., the less negative value of Log(lik)) is a better representation of the data.

Another possible proxy for the goodness of fit can be obtained by comparing the number of observed and predicted counts for various models; the model which comes closer to the observed counts is probably the most reliable. In the example above, the predicted counts exceed the observed ones by 55. Also, the program warns that the fit may be bad in given energy intervals. Thus, most likely this model is incorrect.

We can also plot the spectrum and compare it with the model. To enable the plotting option, type:

```
[rms@kea] gtlikelihood plot=yes &
```

The counts data and model components as a function of energy are in fact written in the default file `counts.dat` in your working directory. This visual inspection allows one to gauge whether adding parameters to a model, or changing the model, leads to an improved representation of the LAT data. The plotting option is automatically included in the python interface of `gtlikelihood`.

We can now run the likelihood again specifying the MINUIT optimizer and using as initial guesses for the parameters the values returned by the previous run with DRMNGB.

This can be accomplished either directly by editing the XML model file or by importing it into ModelEditor.

```
[rms@stone DC2] gtlikelihood
Statistic to use <BINNED|UNBINNED> [UNBINNED] :
Spacecraft file [DC2_FT2.fits] :
Event file [pks0208-events-encut.fits] :
Unbinned exposure map [pks0208-expmap.fits] :
Exposure hypercube file [expCube_full.fits] :
Source model file [pks0208-model.xml] :
Response functions to use <DC2|DC1A|G25> [DC2] :
Optimizer <LBFGS|MINUIT|DRMNGB> [DRMNGB] : MINUIT

 Extragalactic Diffuse:
Prefactor: 2.47513 +/- 0.0269141
Index: -2.1
Scale: 100
Npred: 14379.2

GalProp Diffuse:
Value: 1
Npred: 4638.48

point source 0:
Prefactor: 32.4757 +/- 0.60557
Index: -2.18538 +/- 0.0110863
Scale: 100
```

```
Npred: 8932.21
ROI distance: 0.0311557
TS value: 24335.2
WARNING: Fit may be bad in range [30, 9176.18] (MeV)
WARNING: Fit may be bad in range [22133.6, 34375.4] (MeV)
WARNING: Fit may be bad in range [82916.1, 128776] (MeV)

Total number of observed counts: 27764
Total number of model events: 27949.9

-log(Likelihood): 297349.4376

Elapsed CPU time: 69.11
```

Usually one wants to quote a flux integrated in a given energy band. This option is possible with the python version of `gtlikelihood`. For the interactive version, the flux in 30 MeV – 300 GeV ?? is available as a free parameter (Integral) for the models PowerLaw2 and BrokenPowerlaw2. The units are ph cm^{-2} s^{-1}.

3.2.2. Extracting a light curve

We will use `gtbin` to extract a light curve (in counts) for the AGN. This tool allows only a first look at the data; indeed, no exposure correction is applied, nor is the contribution of the background or other nearby sources considered. Nevertheless, for a bright and/or isolated source `gtbin` provides a reliable way to search for flux variability.

Two input parameters for `gtbin` are the start and stop times of the observations, `TSTART` and `TSTOP`. These must be given in MET - Mission Elapsed Time. To find out what the values of `TSTART` and `TSTOP` are for your data, open the FT1 file with the FTOOl `fv`:

```
[rms@kea] fv pks0208-events-encut.fits&
```

Two windows will appear on the screen, a vertical one with the menu of options, and a horizontal one with the Summary of the FITS file `pks0208-events-encut.fits` (Figure 9). Under the column “Extensions” you will see three entries: Primary, EVENTS, and GTI. The information on the times is contained in the Header of the EVENTS Extension.

Under the “View” column you'll see various buttons; click on the “Header” button to the left of the EVENTS extension. A new pop-up window will appear (Figure 10) which contains a list of keywords. Scrolling down or using the “Find” button, search for the keywords `TSTART` and `TSTOP`, and make a note of the times:

TSTART=220838400

TSTOP=225590400

You can also find these values by using the FTOOL command `fkeyprint`:

```
[rms@kea] fkeyprint "pks0208-events-encut.fits[1]" TSTART

# FILE: pks0208-events-encut.fits[1]
# KEYNAME: TSTART

# EXTENSION:    1
TSTART = 220838400. / mission time of the start of the observation

[rms@kea] fkeyprint "pks0208-events-encut.fits[1]" TSTOP
```

```
# FILE: pks0208-events-encut.fits[1]
# KEYNAME: TSTOP

# EXTENSION:    1
TSTOP = 225590400. / mission time of the end of the observation
```

We are now ready to run gtbin. We will extract a light curve over the 55 days of the simulation with a resolution of 1 day (86400 sec) in the energy range 30 MeV – 300 GeV:

```
[rms@kea] gtbin
This is gtbin version v0r17
Type of output file <CMAP|LC|PHA1|PHA2> [CMAP] : LC
Event data file name [] : pks0208-events-encut.fits
Output file name [] : pks0208-lcurve.fits
Spacecraft data file name [] : DC2_FT2.fits
Algorithm for defining time bins <FILE|LIN|SNR> [LIN] :
Start value for first time bin [] : 220838400
Stop value for last time bin [] : 225590400
Width of linearly uniform time bins [86400] :
[rms@kea]
```

The created light curve is a FITS file that can be manipulated with FTOOLS. We now would like to take a look at the light curve. To do so, we can use fv:

```
[rms@kea] fv pks0208-lcurve.fits &
```

The program will open a menu (vertical panel) and the summary of the FITS file (horizontal panel). As usual, there are three extensions in the file: Primary, RATE, and GTI (Figure 11). The former consists of a Header with basic information on the file - when it was created, etc. The GTI extension contains the Good Time Intervals, i.e., the periods of time in the total exposure where useful data were collected by the detector.

The RATE extension contains the data. To plot the data, click on the `Plot` button under the View column to the right of the RATE extension. This will open another panel listing the FITS file column names on the left: TIME, TIMEDEL, COUNTS, and the plot axes on the right: X, Y, X Error, Y Error. We want to plot COUNTS vs. TIME. To do this, we assign the columns on the left to the axes on the right:

To plot the counts on the Y axis, click first on `COUNTS` and then on `Y`; right beside the axis the name of the column should appear. Similarly, to assign the variable TIME to the X axis, click on `TIME` and then on `X`. To start the plot, click on `GO`. A panel will appear with the plot of COUNTS versus TIME, as in Figure 12.

Under "Edit-Preferences" you can customize the plot by selecting the background color, the font, the symbols, etc. For a hardcopy, go to the pull-down menu File in the plot window and select Print. A new window will appear with the light curve. From this one, select Print and follow the instructions in the pop-up window.

Energy-dependent light curves: To investigate variability as a function of energy, we may want to extract LAT light curves in selected energy bins. We can accomplish this in two simple steps:

- with `gtselect`, extract an FT1 file in the desired energy range

- using `gtbin`, extract the light curve as discussed above.

3.2.3. *Time-dependent spectra*

You may also want to extract spectra on selected time intervals, to investigate the spectral variability of the source. For example, in the case of PKS 0208 let's say we want to extract the LAT spectrum during the final flare starting day 40 and ending day 50. Here are the steps:

- First, we need to determine the start and end time in MET. To this end, note that in the `fv` plot it is possible to read the abscissa and ordinate values directly from the image, by positioning the cursor on the desired location in the graph. The value of the coordinates will be displayed in the "Graph Coordinates" box at the top-left of the chart.

- Then, using `gtselect` we extract an FT1 FITS file in selected the time period.

- Repeat the steps in § 3.3 to fit the time-resolved spectrum.

4. Case study 2: AGN in a crowded field

In this example we will consider the case of a bright AGN surrounded by other bright LAT point sources. The basic issue is the following: due to the width of the PSF especially at lower energies, significant contribution to the AGN flux will be present from the nearby sources. This is where the power of the maximum likelihood, which allows one to perform simultaneous spatial and spectral modeling of the selected field, comes into play.

4.1. Determining the sources in the field

We will use the case of 3C 279 for this example. Figure 13 shows the LAT image in an extraction region of 20 degrees, `3c279-20deg.fits`. Several point sources are apparent in the AGN neighborood.

To find out exactly how many point sources are present in the field above the detection limit, we will use here the DC2 source catalog previously downloaded (§ 2); in real life one should use a detection algorithm for point sources. The use of the DC2 catalog requires accumulating an image in counts and sky coordinates, which can be done with `gtbin`:

```
[rms@kea] gtbin
This is gtbin version v0r16p3
Type of output file <CMAP|LC|PHA1|PHA2> [LC] : CMAP
Event data file name [] : 3c279-20deg.fits
Output file name [] : 3c279-cmap.fits
Spacecraft data file name [] : DC2_FT2.fits
Size of the X axis in pixels [500] :
Size of the Y axis in pixels [500] :
Image scale (in degrees/pixel) [0.1] :
Coordinate system (CEL - celestial, GAL -galactic) <CEL|GAL> [CEL] :
First coordinate of image center in degrees (RA or galactic l)[] : 194.07
Second coordinate of image center in degrees (DEC or galactic b)[] : -5.789
Rotation angle of image axis, in degrees [0] :
```

We use a square image of 500x500 pixels with a rebinning factor 0.1. Figure 14 shows the counts image. Note that the counts image is the mirror of the FT1 image because....

We can now load the LAT DC2 catalog. In the ds9 image click on the “Region” button either on the top or in the menu in the middle; select “Load Regions” or just “Load”. The pop-up window will ask for the name of the catalog, `LATSourceCatalog_v1.reg`. The sources will be marked by crosses (Figure 15).

Ideally, it should be possible to write the coordinates of the sources in the field into a file. Unfortunately, this option is still not available ??? To find the RA, DEC of the sources in the field, position the cursor on top of the marked cross and read the coordinates (α, δ) from the "FK5" field of the ds9 window at the top-left. You will need these values, converted in degrees, as input for the spatial models in `ModelEditor`.

In Figure 14, note the presence of a bright point source within 3 degrees of 3C 279. This does not have an obvious counterpart in NED, and for future reference we will call this source AGN1.

4.2. Spectral analysis

We now want to analyze the LAT spectrum of 3C 279. The basic steps of the spectral analysis are similar to the case of an isolated AGN:

1) select the optimal energy range;

2) create an exposure map (`gtexpmap`);

3) create the source model in an XML file (`ModelEditor`);

4) create the diffuse emission responses (`gtdiffresp`);

5) run max likelihood (`gtlikelihood`).

The main difference with the case of an isolated bright AGN is in step 3. Here, we will need to explicitly include the sources nearby the AGN by specifying a spectral and spatial model for each one. This is accomplished under ModelEditor by using the "Add new point source" under the Edit function, and specifying the spectral and spatial model as described above.

Once the maximum likelihood returns the estimated parameters, we can plot the data (spectra and models) from the `counts.dat` file. The contributions from the various sources in the field and of the backgrounds, as well as the total summed spectrum, can be inspected. By fixing the parameters of the other components and varying those of a given source, one can evaluate the model for a source of interest.

4.3. Timing analysis

As discussed above, in the case of an isolated bright AGN the tool `gtbin` can be used to extract a crude, but rather reliable, light curve of the source. This is not the case, however, for a bright AGN surrounded by one or more sources, or for a weak AGN where background subtraction becomes important.

One way to create the light curve for the AGN is to extract its time-resolved flux with maximum likelihood, by extracting time-resolved FT1 files and following the steps outlined in § 3.2.1. In practice this method is too tedious to be performed manually; use of scripts to run the tools in succession is strongly suggested. Unfortunately, this is also a time-consuming procedure, the longest-running step consisting of the extraction of the livetimecubes for each selected time interval. Depending on the size of the FT1 file, the complexity of the model, and the time resolution, approximate run time for the whole precedure can vary from several minutes to over an hour for most desktop computers.

Figure 16b shows the light curve in 30 MeV – 300 GeV of 3C 279 obtained from such a script with a resolution of 1 day. For comparison, we also plot the curve obtained from a “blind” extractor such as `gtbin` in Figure 16a, while Figure 16c shows the light curve of AGN1 which is also produced by the script. Comparing the light curves in the three panels shows the power of the maximum likelihood method for sorting out the contributions from the various sources; for example, the first flare in the `gtbin`-extracted curve of 3C 279 (Fig.

16a) turns out to be due to the variable nearby AGN1 (Fig. 16c), and not to 3C 279.

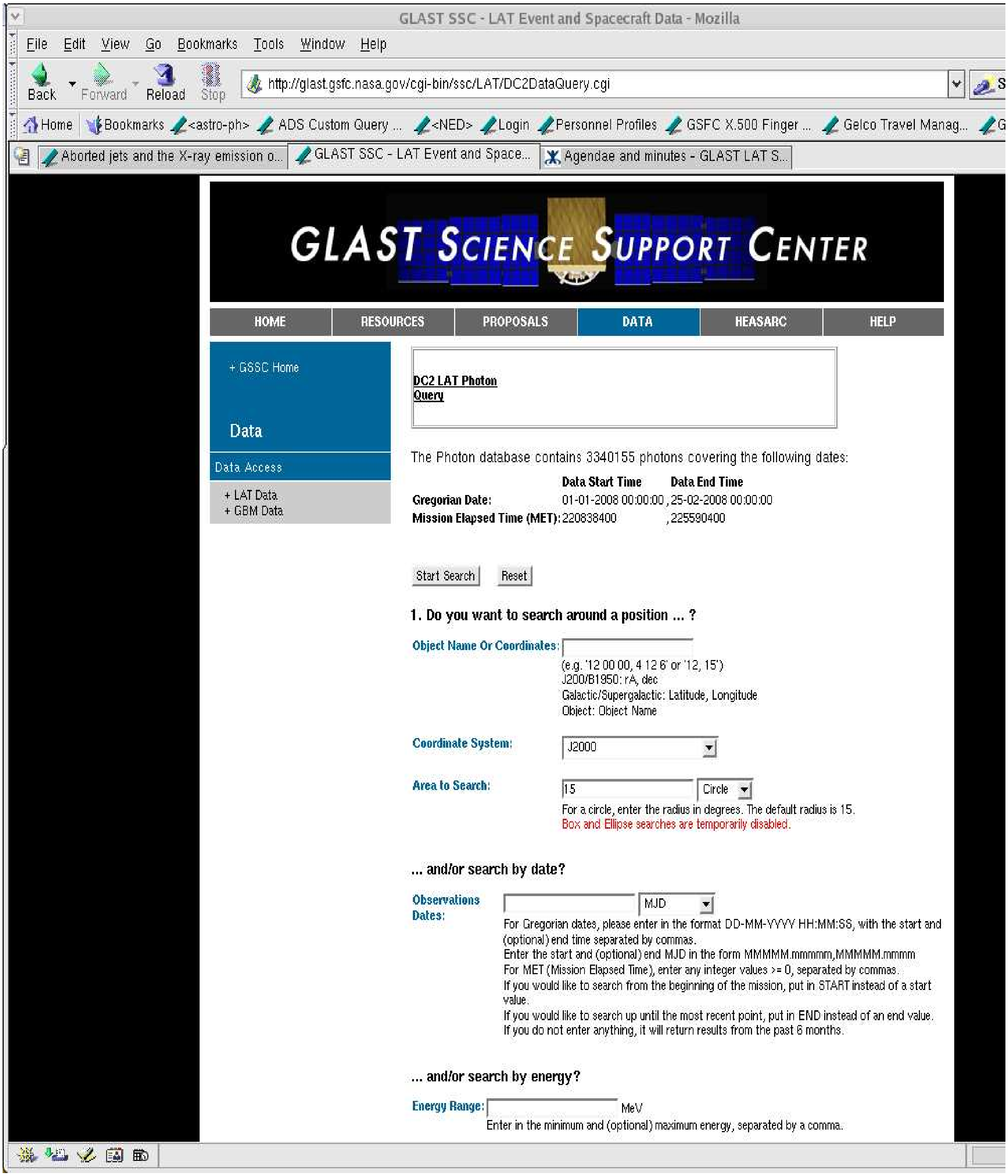

GLAST SSC - LAT Event and Spacecraft Data - Mozilla
File Edit View Go Bookmarks Tools Window Help
Back Forward Reload Stop
http://glast.gsfc.nasa.gov/cgi-bin/ssc/LAT/DC2DataQuery.cgi
Home Bookmarks <astro-ph> ADS Custom Query ... <NED> Login Personnel Profiles GSFC X.500 Finger ... Gelco Travel Manag...
Aborted jets and the X-ray emission o...
GLAST SSC - LAT Event and Space...
Agendae and minutes - GLAST LAT S...
GLAST SCIENCE SUPPORT CENTER
HOME
RESOURCES
PROPOSALS
DATA
HEASARC
HELP
+ GSSC Home
Data
Data Access
+ LAT Data
+ GBM Data
DC2 LAT Photon Query
The Photon database contains 3340155 photons covering the following dates:
Data Start Time
Data End Time
Gregorian Date: 01-01-2008 00:00:00 , 25-02-2008 00:00:00
Mission Elapsed Time (MET): 220838400 , 225590400
Start Search
Reset
1. Do you want to search around a position ... ?
Object Name Or Coordinates:
(e.g. '12 00 00, 4 12 6' or '12, 15')
J200/B1950: rA, dec
Galactic/Supergalactic: Latitude, Longitude
Object: Object Name
Coordinate System:
J2000
Area to Search:
15
Circle
For a circle, enter the radius in degrees. The default radius is 15.
Box and Ellipse searches are temporarily disabled.
... and/or search by date?
Observations Dates:
MJD
For Gregorian dates, please enter in the format DD-MM-YYYY HH:MM:SS, with the start and (optional) end time separated by commas.
Enter the start and (optional) end MJD in the form MMMMM.mmmmm,MMMMM.mmmm
For MET (Mission Elapsed Time), enter any integer values >= 0, separated by commas.
If you would like to search from the beginning of the mission, put in START instead of a start value.
If you would like to search up until the most recent point, put in END instead of an end value.
If you do not enter anything, it will return results from the past 6 months.
... and/or search by energy?
Energy Range:
MeV
Enter in the minimum and (optional) maximum energy, separated by a comma.

Fig. 1.—

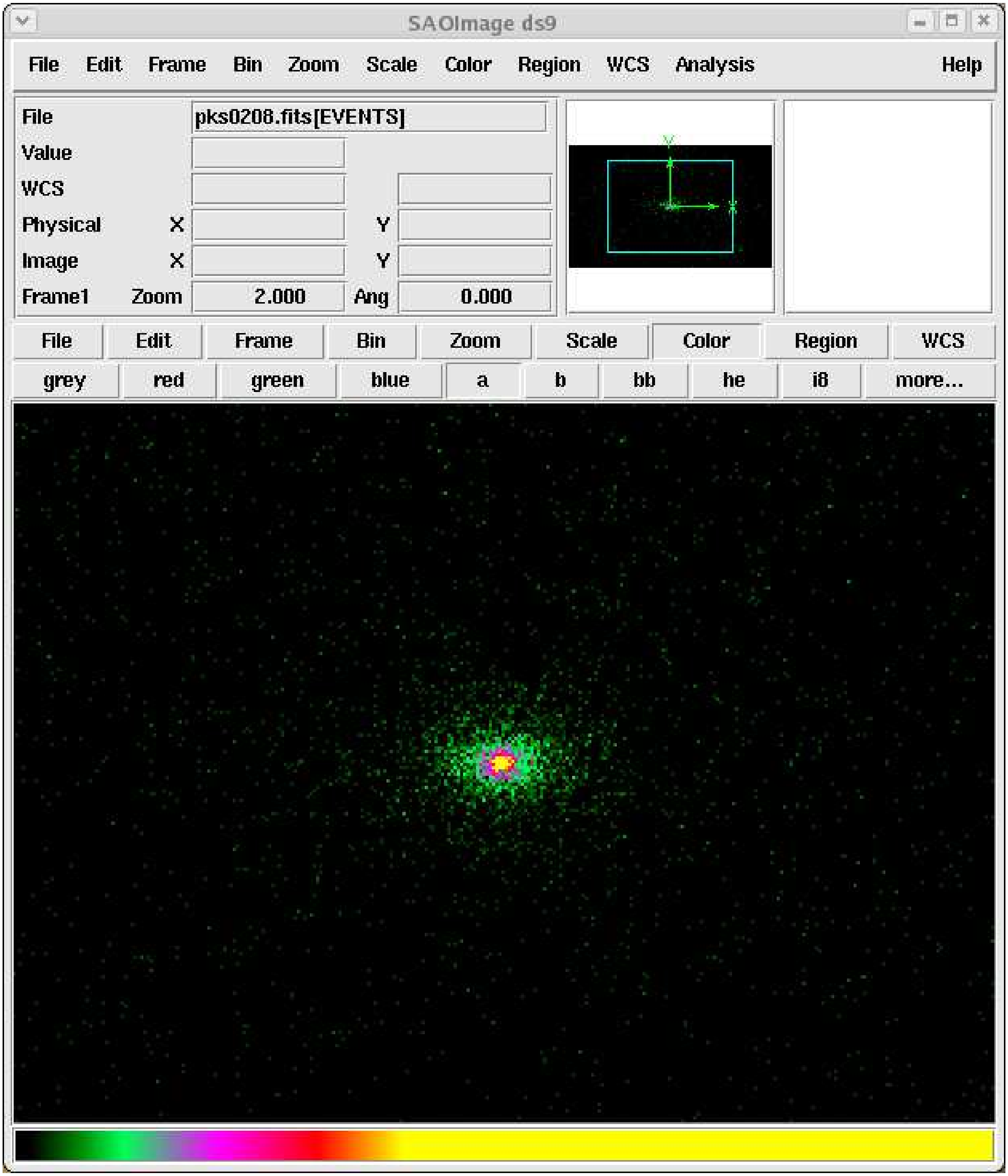

SAOImage ds9
File Edit Frame Bin Zoom Scale Color Region WCS Analysis Help
File pks0208.fits[EVENTS]
Value
WCS
Physical X Y
Image X Y
Frame1 Zoom 2.000 Ang 0.000
File Edit Frame Bin Zoom Scale Color Region WCS
grey red green blue a b bb he i8 more...

Fig. 2.—

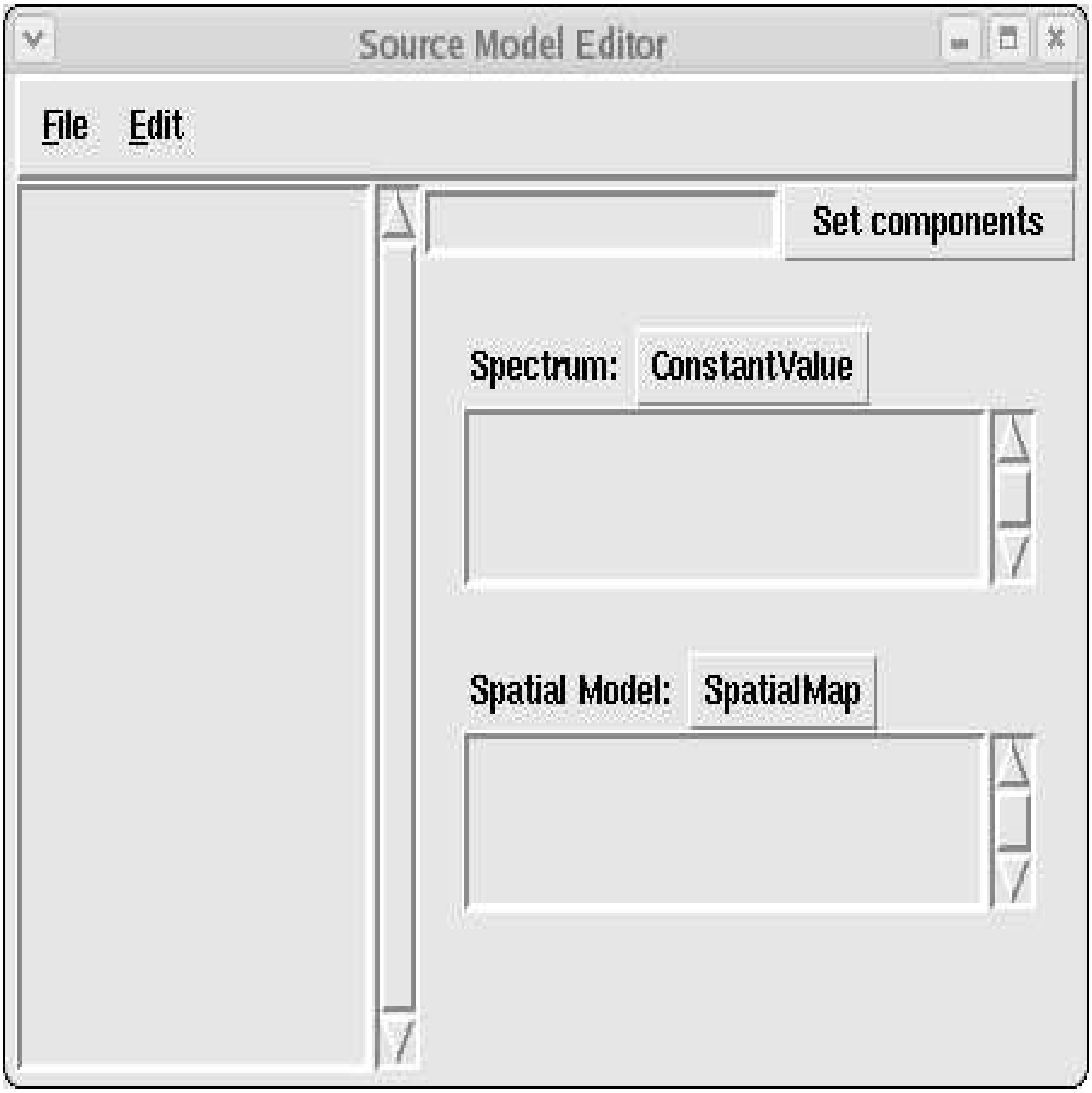

Source Model Editor
File
Edit
Set components
Spectrum:
ConstantValue
Spatial Model:
SpatialMap

Fig. 3.—

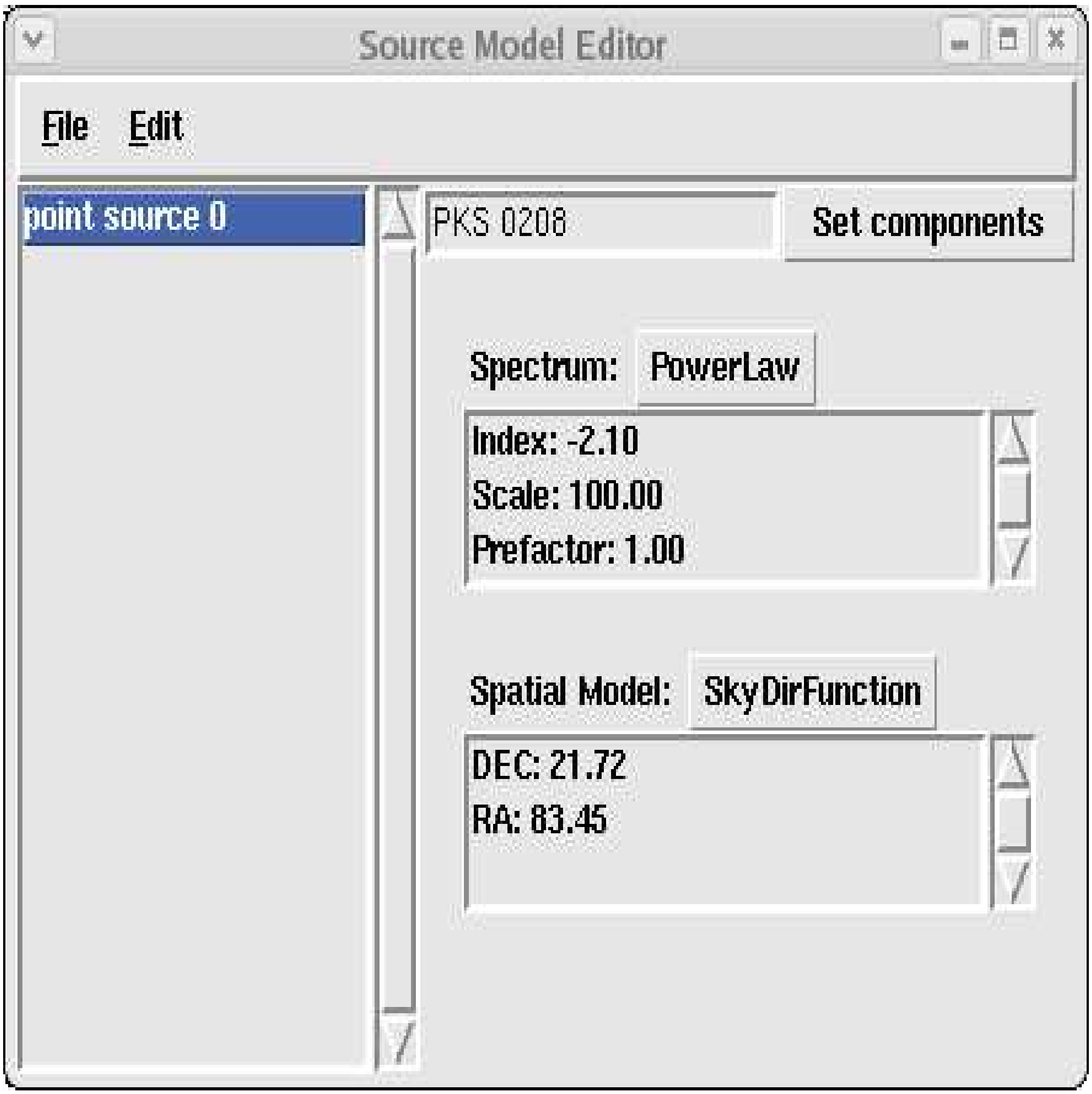

Source Model Editor
File
Edit
point source 0
PKS 0208
Set components
Spectrum:
PowerLaw
Index: -2.10
Scale: 100.00
Prefactor: 1.00
Spatial Model:
SkyDirFunction
DEC: 21.72
RA: 83.45

Fig. 4.—

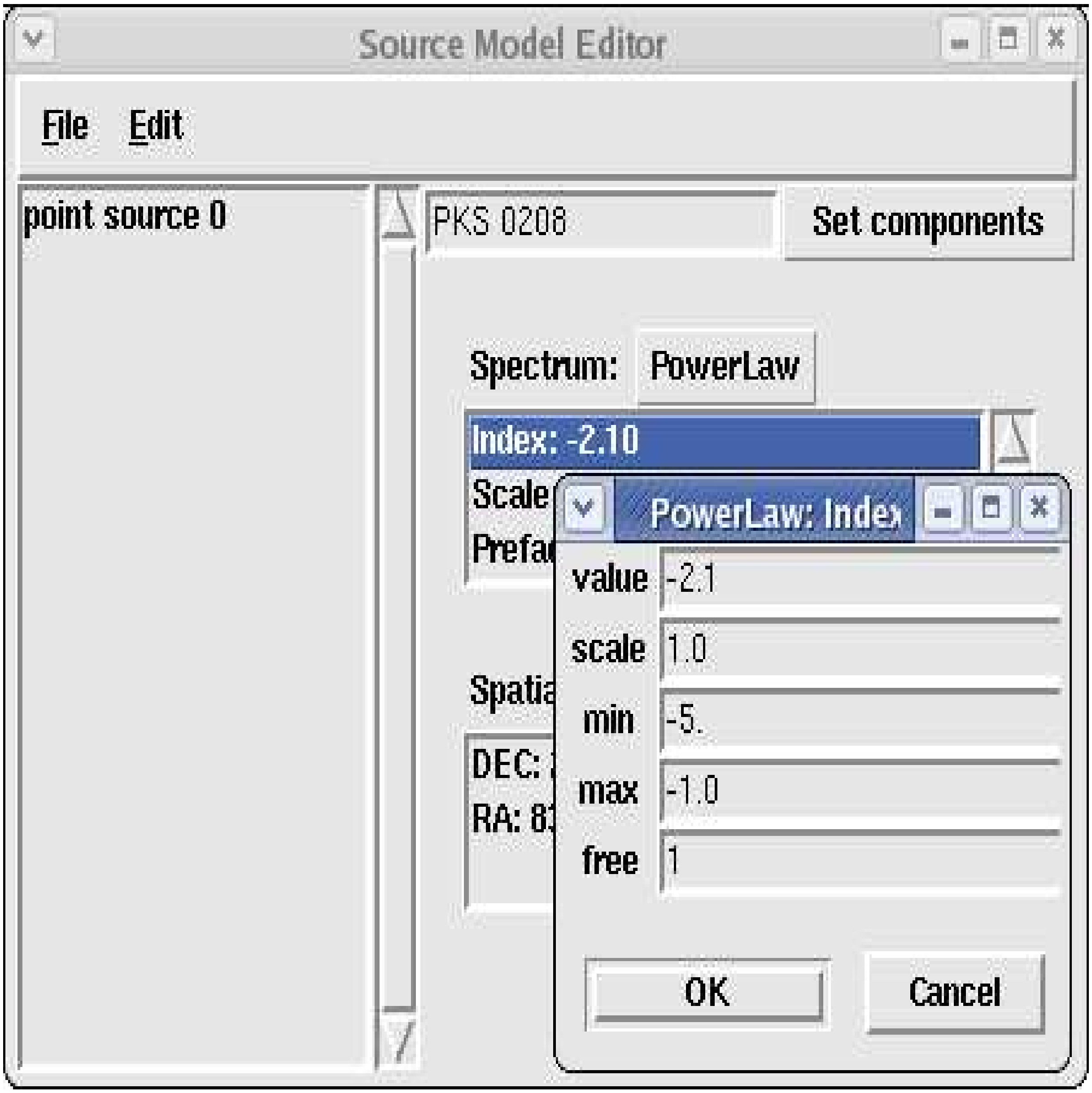
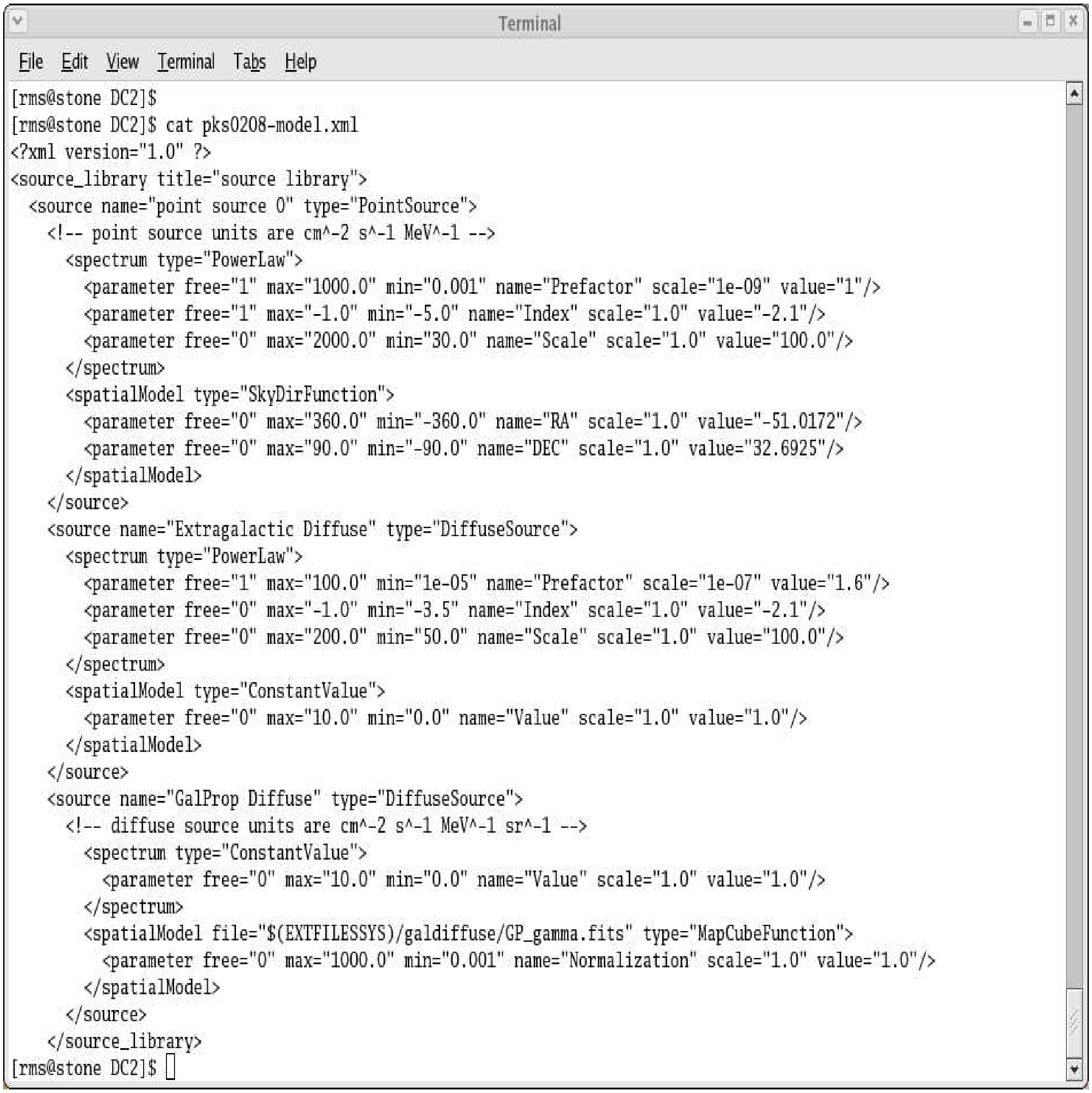

Source Model Editor
File
Edit
point source 0
PKS 0208
Set components
Spectrum:
PowerLaw
Index: -2.10
Scale
Prefa
PowerLaw: Index
value
-2.1
scale
1.0
min
-5.
max
-1.0
free
1
Spatia
DEC:
RA: 8
OK
Cancel

Fig. 5.—



Terminal

File Edit View Terminal Tabs Help

```
[rms@stone DC2]$
[rms@stone DC2]$ cat pks0208-model.xml
<?xml version="1.0" ?>
<source_library title="source library">
  <source name="point source 0" type="PointSource">
    <!-- point source units are cm^-2 s^-1 MeV^-1 -->
      <spectrum type="PowerLaw">
        <parameter free="1" max="1000.0" min="0.001" name="Prefactor" scale="1e-09" value="1"/>
        <parameter free="1" max="-1.0" min="-5.0" name="Index" scale="1.0" value="-2.1"/>
        <parameter free="0" max="2000.0" min="30.0" name="Scale" scale="1.0" value="100.0"/>
      </spectrum>
      <spatialModel type="SkyDirFunction">
        <parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="-51.0172"/>
        <parameter free="0" max="90.0" min="-90.0" name="DEC" scale="1.0" value="32.6925"/>
      </spatialModel>
    </source>
    <source name="Extragalactic Diffuse" type="DiffuseSource">
      <spectrum type="PowerLaw">
        <parameter free="1" max="100.0" min="1e-05" name="Prefactor" scale="1e-07" value="1.6"/>
        <parameter free="0" max="-1.0" min="-3.5" name="Index" scale="1.0" value="-2.1"/>
        <parameter free="0" max="200.0" min="50.0" name="Scale" scale="1.0" value="100.0"/>
      </spectrum>
      <spatialModel type="ConstantValue">
        <parameter free="0" max="10.0" min="0.0" name="Value" scale="1.0" value="1.0"/>
      </spatialModel>
    </source>
    <source name="GalProp Diffuse" type="DiffuseSource">
      <!-- diffuse source units are cm^-2 s^-1 MeV^-1 sr^-1 -->
        <spectrum type="ConstantValue">
          <parameter free="0" max="10.0" min="0.0" name="Value" scale="1.0" value="1.0"/>
        </spectrum>
        <spatialModel file="$(EXTFILESSYS)/galdiffuse/GP_gamma.fits" type="MapCubeFunction">
          <parameter free="0" max="1000.0" min="0.001" name="Normalization" scale="1.0" value="1.0"/>
        </spatialModel>
      </source>
    </source_library>
[rms@stone DC2]$
```

Fig. 6.—

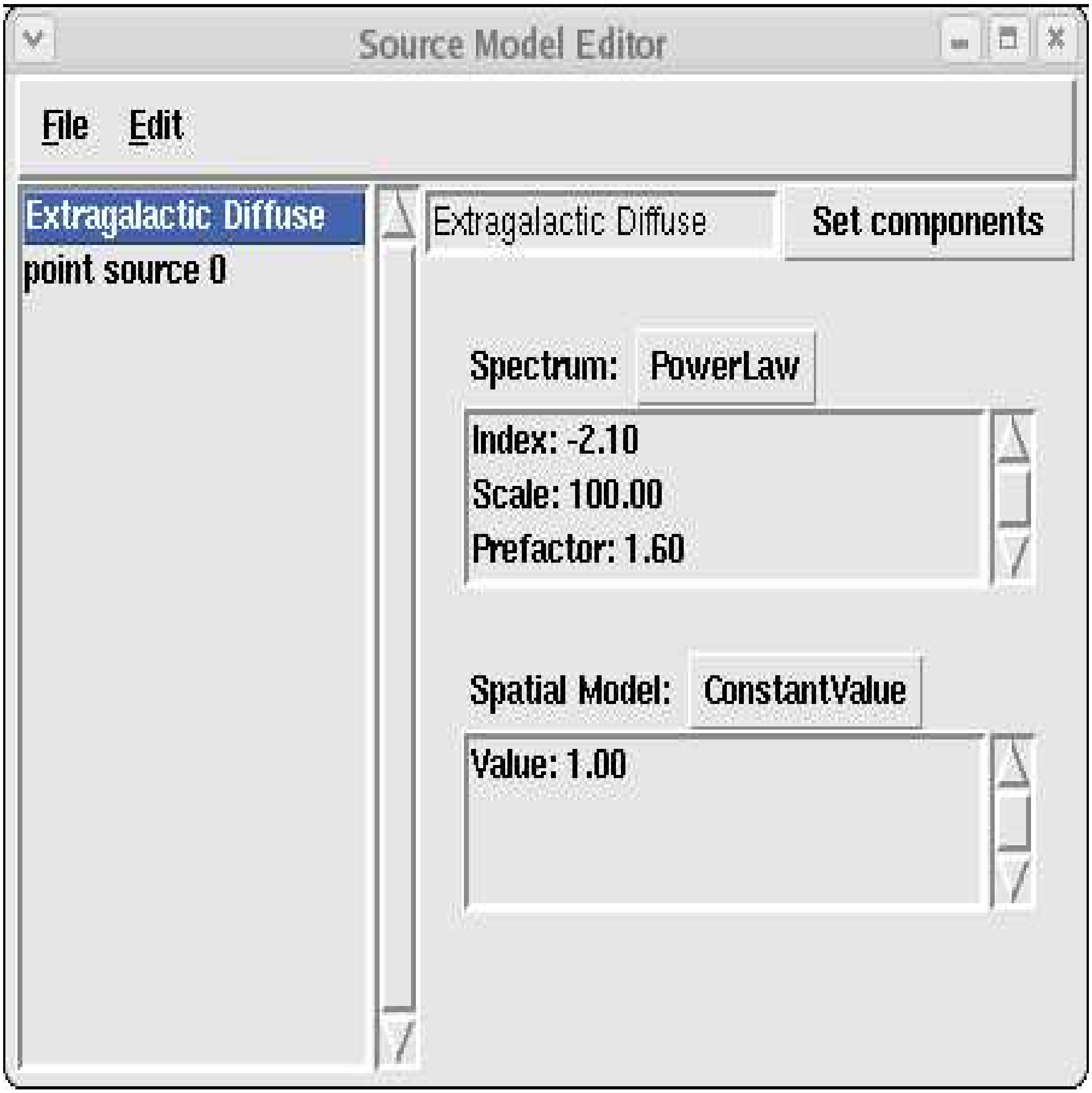

Source Model Editor
File
Edit
Extragalactic Diffuse
point source 0
Extragalactic Diffuse
Set components
Spectrum:
PowerLaw
Index: -2.10
Scale: 100.00
Prefactor: 1.60
Spatial Model:
ConstantValue
Value: 1.00

Fig. 7.—

```
[rms@stone DC2]$
[rms@stone DC2]$ cat pks0208-model.xml
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<source_library title="source library">
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    <!-- point source units are cm^-2 s^-1 MeV^-1 -->
      <spectrum type="PowerLaw">
        <parameter free="1" max="1000.0" min="0.001" name="Prefactor" scale="1e-09" value="1"/>
        <parameter free="1" max="-1.0" min="-5.0" name="Index" scale="1.0" value="-2.1"/>
        <parameter free="0" max="2000.0" min="30.0" name="Scale" scale="1.0" value="100.0"/>
      </spectrum>
      <spatialModel type="SkyDirFunction">
        <parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="-51.0172"/>
        <parameter free="0" max="90.0" min="-90.0" name="DEC" scale="1.0" value="32.6925"/>
      </spatialModel>
    </source>
    <source name="Extragalactic Diffuse" type="DiffuseSource">
      <spectrum type="PowerLaw">
        <parameter free="1" max="100.0" min="1e-05" name="Prefactor" scale="1e-07" value="1.6"/>
        <parameter free="0" max="-1.0" min="-3.5" name="Index" scale="1.0" value="-2.1"/>
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      </spectrum>
      <spatialModel type="ConstantValue">
        <parameter free="0" max="10.0" min="0.0" name="Value" scale="1.0" value="1.0"/>
      </spatialModel>
    </source>
    <source name="GalProp Diffuse" type="DiffuseSource">
      <!-- diffuse source units are cm^-2 s^-1 MeV^-1 sr^-1 -->
        <spectrum type="ConstantValue">
          <parameter free="0" max="10.0" min="0.0" name="Value" scale="1.0" value="1.0"/>
        </spectrum>
        <spatialModel file="$(EXTFILESSYS)/galdiffuse/GP_gamma.fits" type="MapCubeFunction">
          <parameter free="0" max="1000.0" min="0.001" name="Normalization" scale="1.0" value="1.0"/>
        </spatialModel>
      </source>
    </source_library>
[rms@stone DC2]$
```

Fig. 8.—

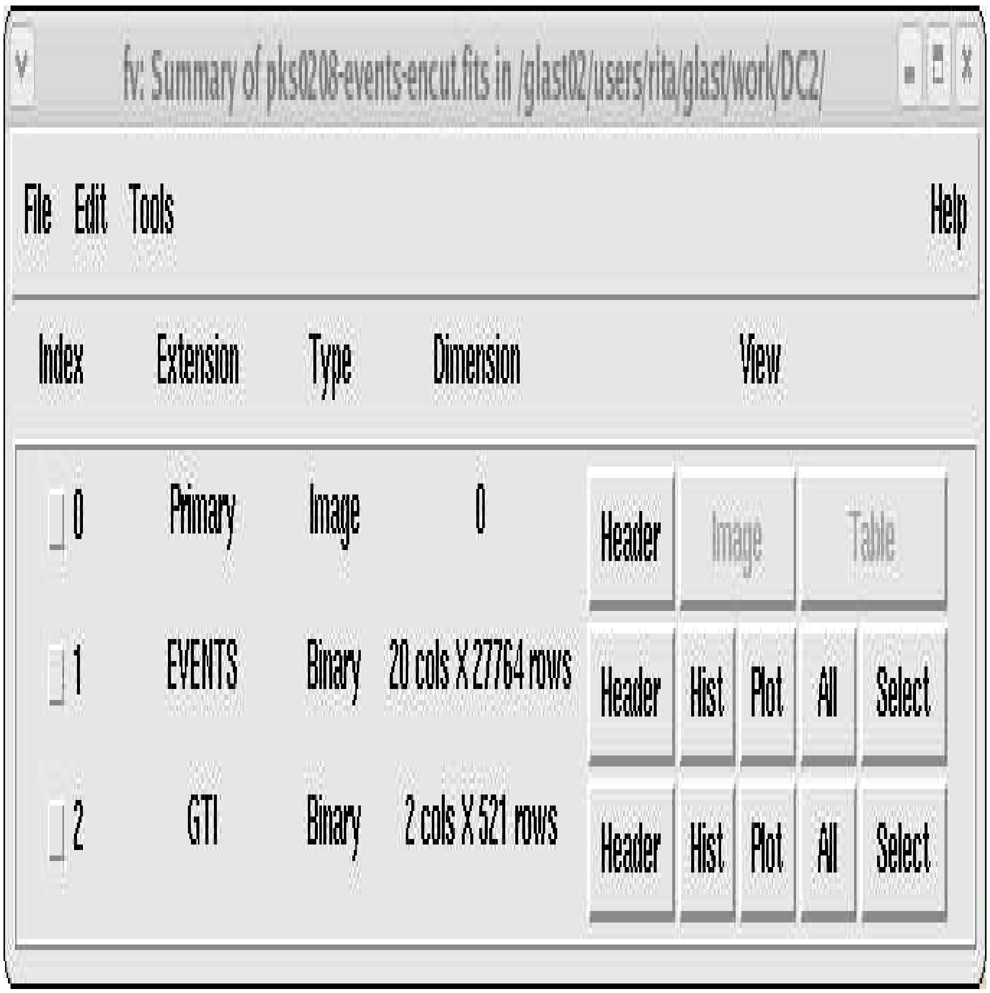

fv: Summary of pks0208-events-encut.fits in /glast02/users/rita/glast/work/DC2/
File
Edit
Tools
Help
Index
Extension
Type
Dimension
View
0
Primary
Image
0
Header
Image
Table
1
EVENTS
Binary
20 cols X 27764 rows
Header
Hist
Plot
All
Select
2
GTI
Binary
2 cols X 521 rows
Header
Hist
Plot
All
Select

Fig. 9.—

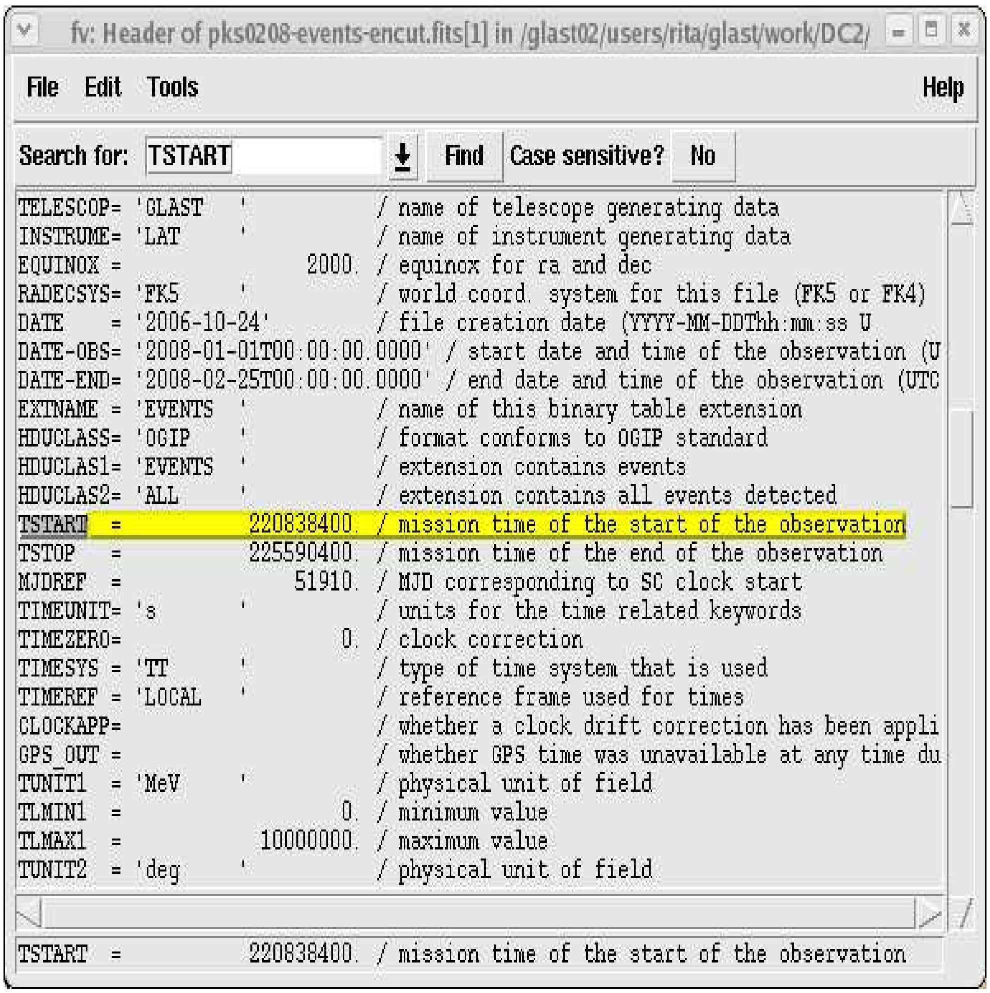

fv: Header of pks0208-events-encut.fits[1] in /glast02/users/rita/glast/work/DC2/
File Edit Tools
Help
Search for: TSTART
Find
Case sensitive? No
TELESCOP= 'GLAST ' / name of telescope generating data
INSTRUME= 'LAT ' / name of instrument generating data
EQUINOX = 2000. / equinox for ra and dec
RADECSYS= 'FK5 ' / world coord. system for this file (FK5 or FK4)
DATE = '2006-10-24' / file creation date (YYYY-MM-DDThh:mm:ss U
DATE-OBS= '2008-01-01T00:00:00.0000' / start date and time of the observation (U
DATE-END= '2008-02-25T00:00:00.0000' / end date and time of the observation (UTC
EXTNAME = 'EVENTS ' / name of this binary table extension
HDUCLASS= 'OGIP ' / format conforms to OGIP standard
HDUCLAS1= 'EVENTS ' / extension contains events
HDUCLAS2= 'ALL ' / extension contains all events detected
TSTART = 220838400. / mission time of the start of the observation
TSTOP = 225590400. / mission time of the end of the observation
MJDREF = 51910. / MJD corresponding to SC clock start
TIMEUNIT= 's ' / units for the time related keywords
TIMEZERO= 0. / clock correction
TIMESYS = 'TT ' / type of time system that is used
TIMEREF = 'LOCAL ' / reference frame used for times
CLOCKAPP= / whether a clock drift correction has been appli
GPS_OUT = / whether GPS time was unavailable at any time du
TUNIT1 = 'MeV ' / physical unit of field
TLMIN1 = 0. / minimum value
TLMAX1 = 10000000. / maximum value
TUNIT2 = 'deg ' / physical unit of field
TSTART = 220838400. / mission time of the start of the observation

Fig. 10.—

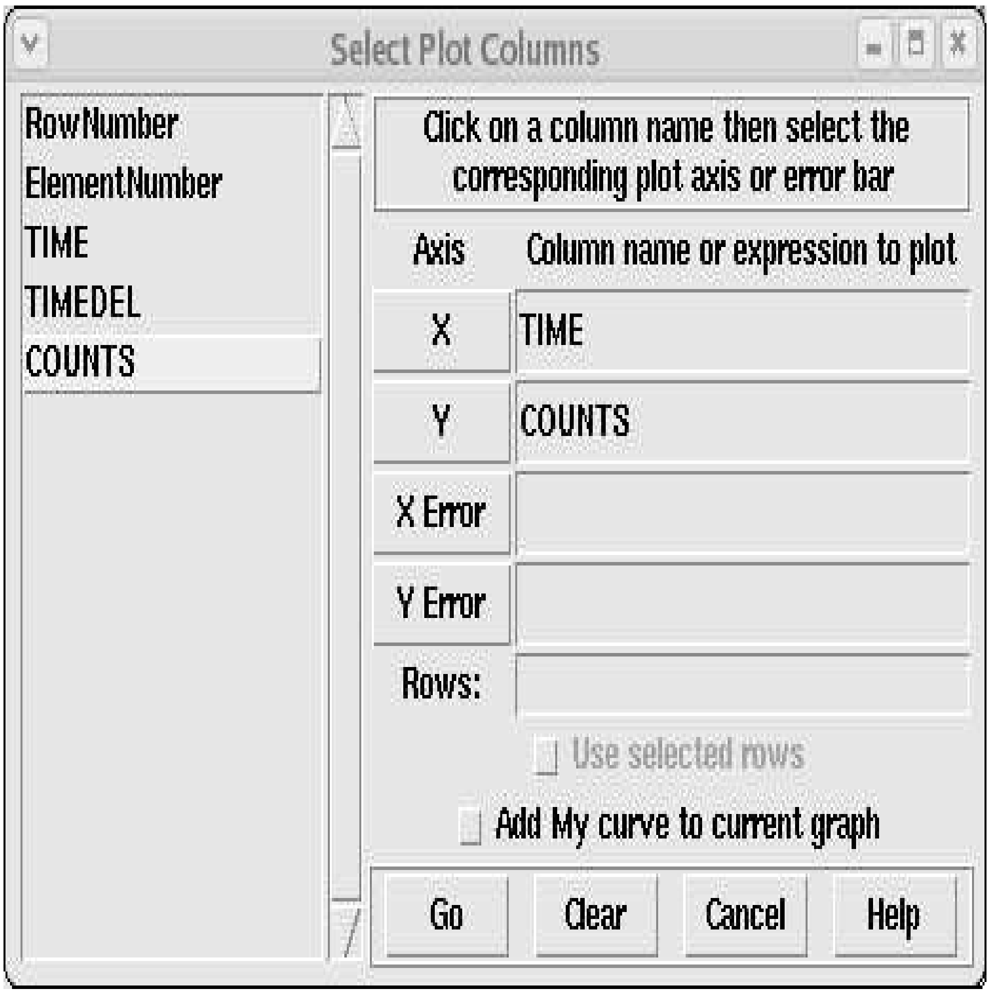

Select Plot Columns
RowNumber
ElementNumber
TIME
TIMEDEL
COUNTS
Click on a column name then select the corresponding plot axis or error bar
Axis
Column name or expression to plot
X
TIME
Y
COUNTS
X Error
Y Error
Rows:
Use selected rows
Add My curve to current graph
Go
Clear
Cancel
Help

Fig. 11.—

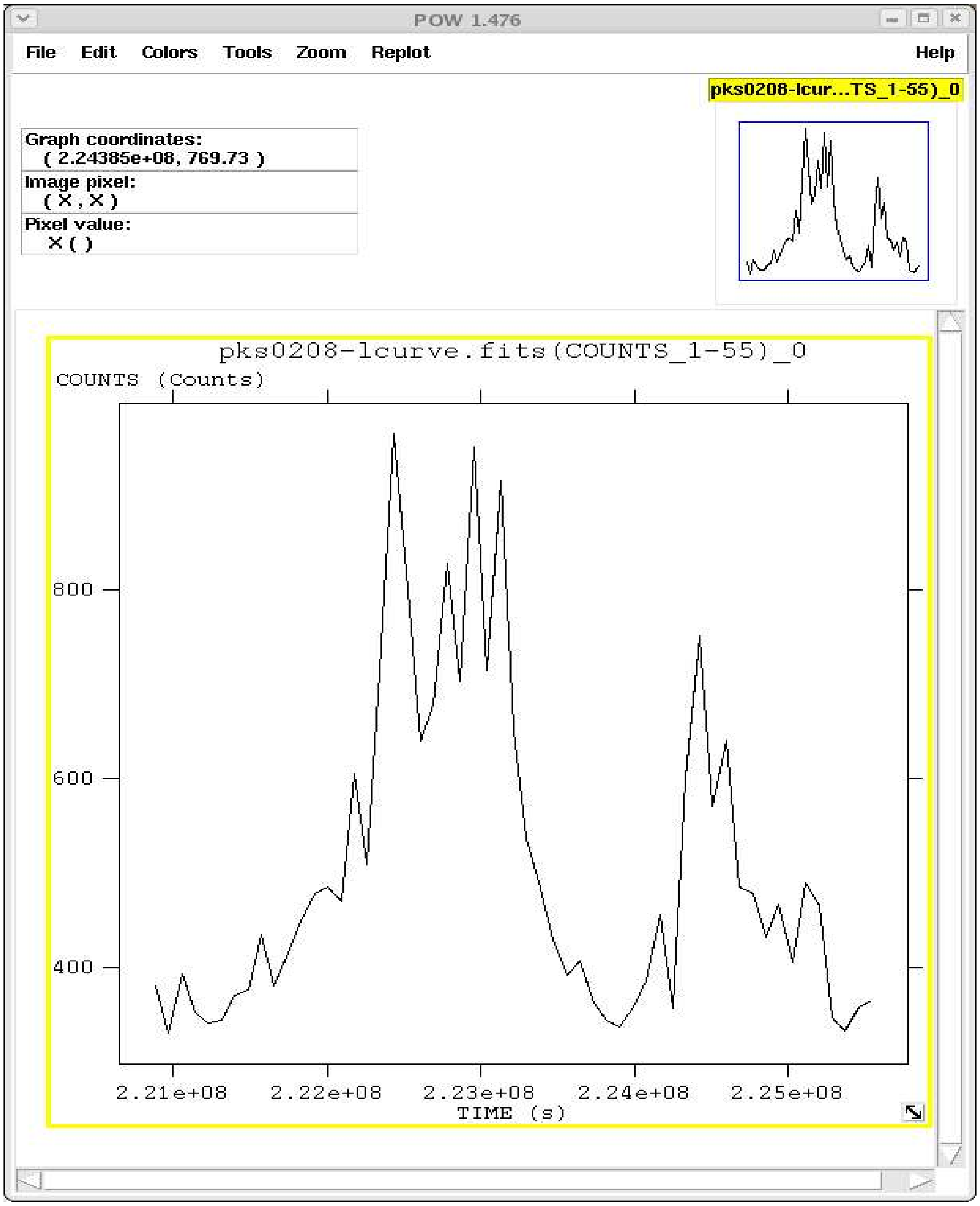
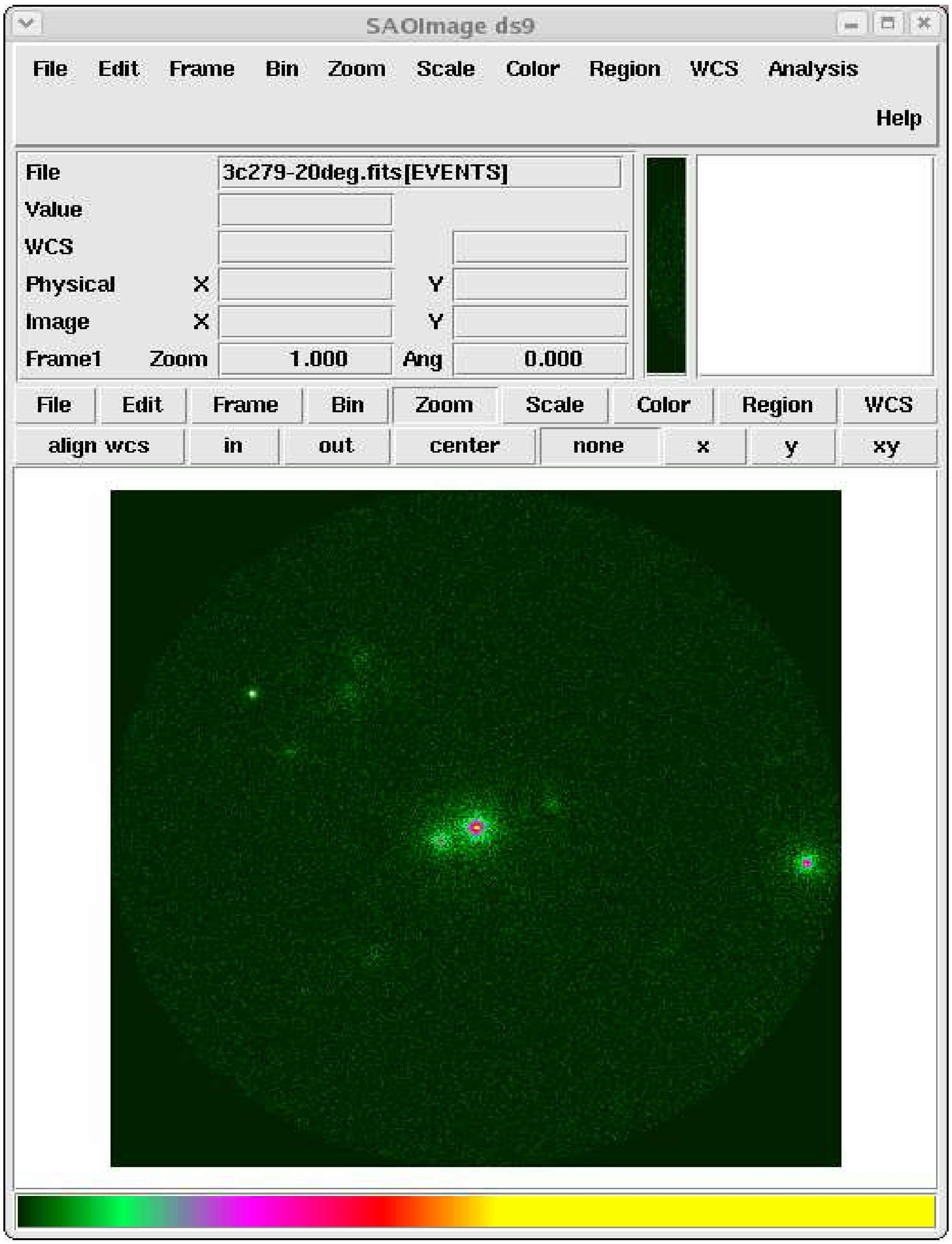

POW 1.476
File Edit Colors Tools Zoom Replot Help
pks0208-lcur...TS_1-55)_0
Graph coordinates:
(2.24385e+08, 769.73)
Image pixel:
(X , X)
Pixel value:
X ( )
pks0208-lcurve.fits(COUNTS_1-55)_0
COUNTS (Counts)
800
600
400
2.21e+08
2.22e+08
2.23e+08
2.24e+08
2.25e+08
TIME (s)

Fig. 12.—


SAOImage ds9
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Help
File 3c279-20deg.fits[EVENTS]
Value
WCS
Physical X Y
Image X Y
Frame1 Zoom 1.000 Ang 0.000
File Edit Frame Bin Zoom Scale Color Region WCS
align wcs in out center none x y xy

Fig. 13.—

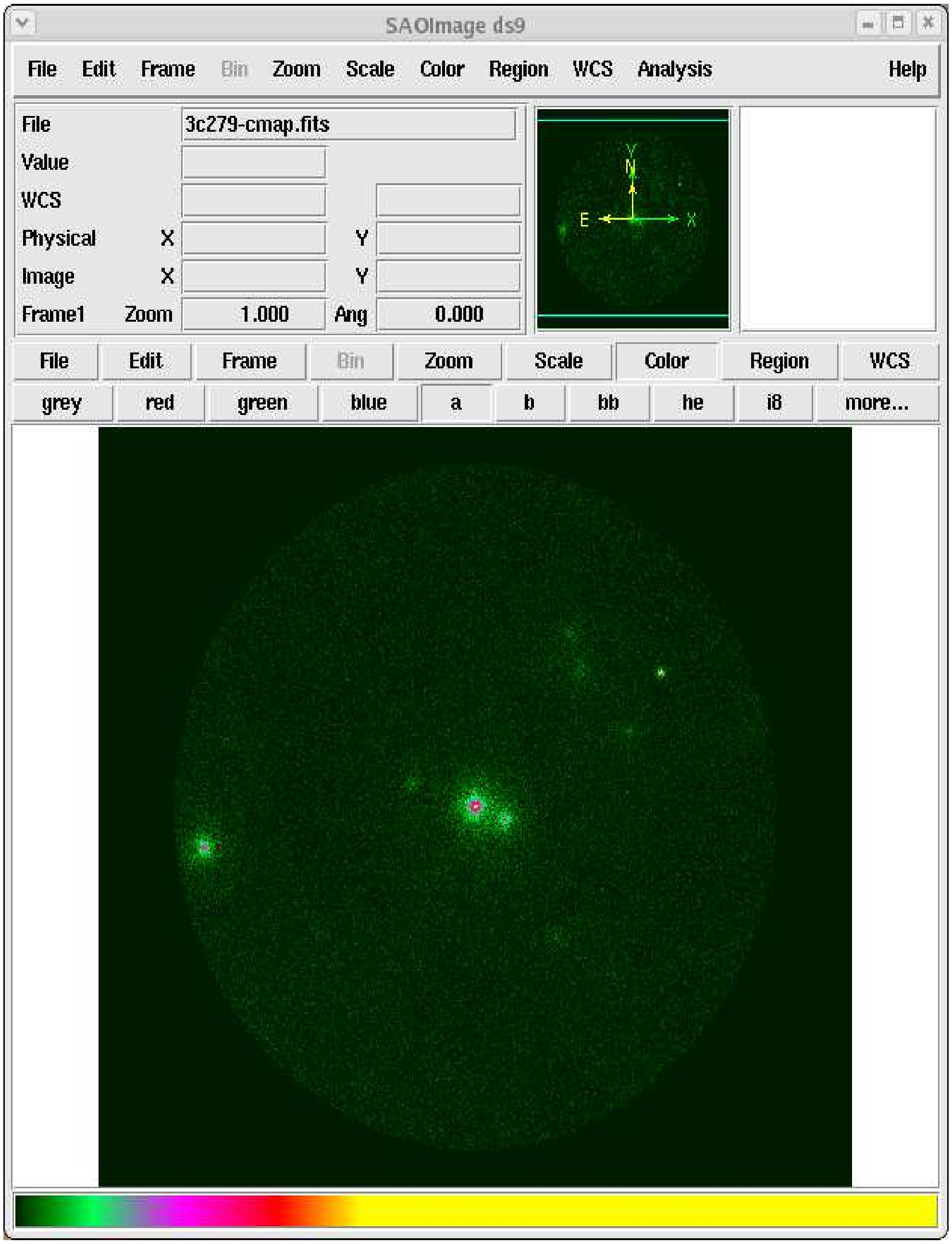
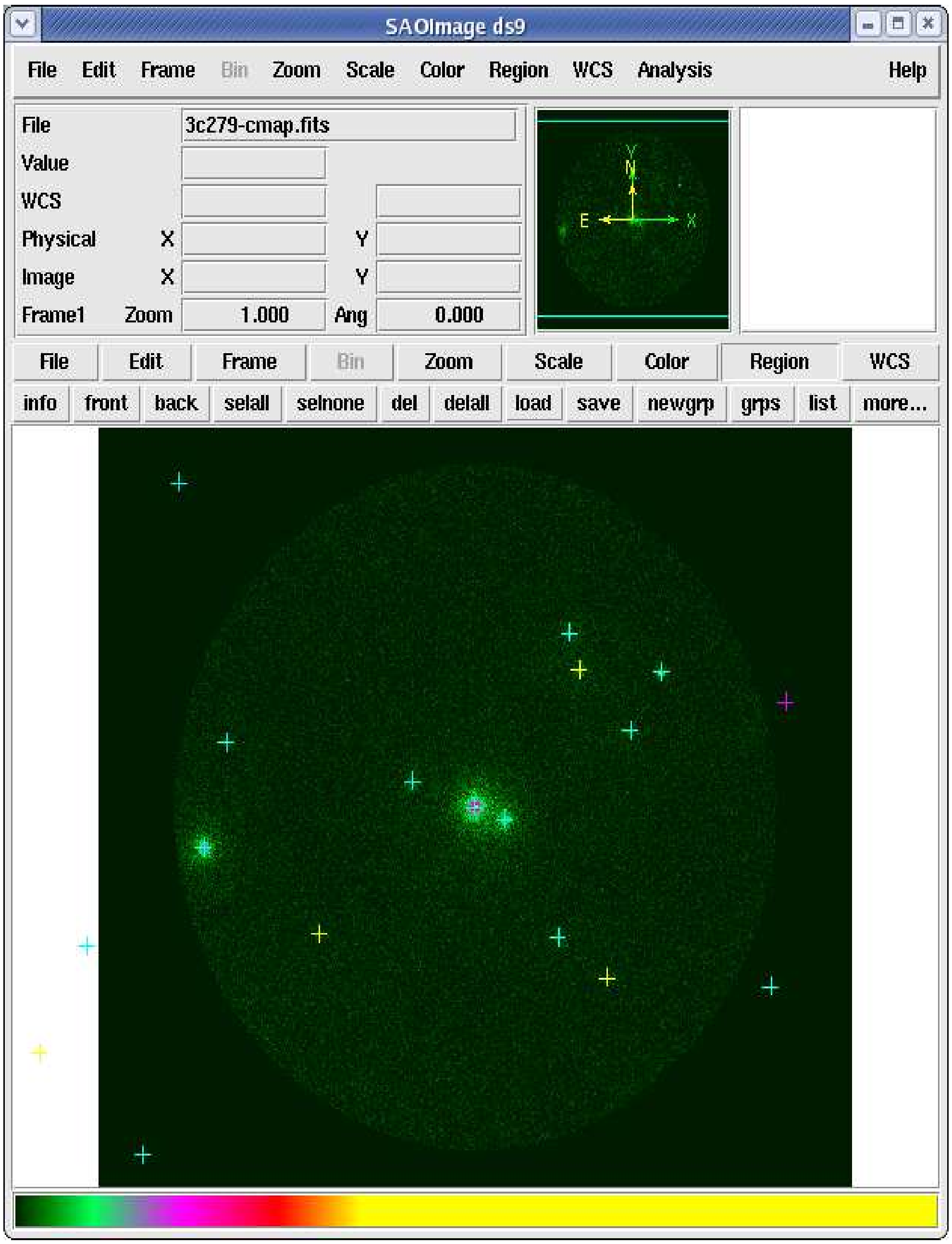

SAOImage ds9
File
Edit
Frame
Bin
Zoom
Scale
Color
Region
WCS
Analysis
Help
File
3c279-cmap.fits
Value
WCS
Physical
X
Y
Image
X
Y
Frame1
Zoom
1.000
Ang
0.000
N
E
X
Y
File
Edit
Frame
Bin
Zoom
Scale
Color
Region
WCS
grey
red
green
blue
a
b
bb
he
i8
more...

Fig. 14.—


SAOImage ds9
File
Edit
Frame
Bin
Zoom
Scale
Color
Region
WCS
Analysis
Help
File
3c279-cmap.fits
Value
WCS
Physical
X
Y
Image
X
Y
Frame1
Zoom
1.000
Ang
0.000
N
Y
E
X
File
Edit
Frame
Bin
Zoom
Scale
Color
Region
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front
back
selall
selnone
del
delall
load
save
newgrp
grps
list
more...

Fig. 15.—

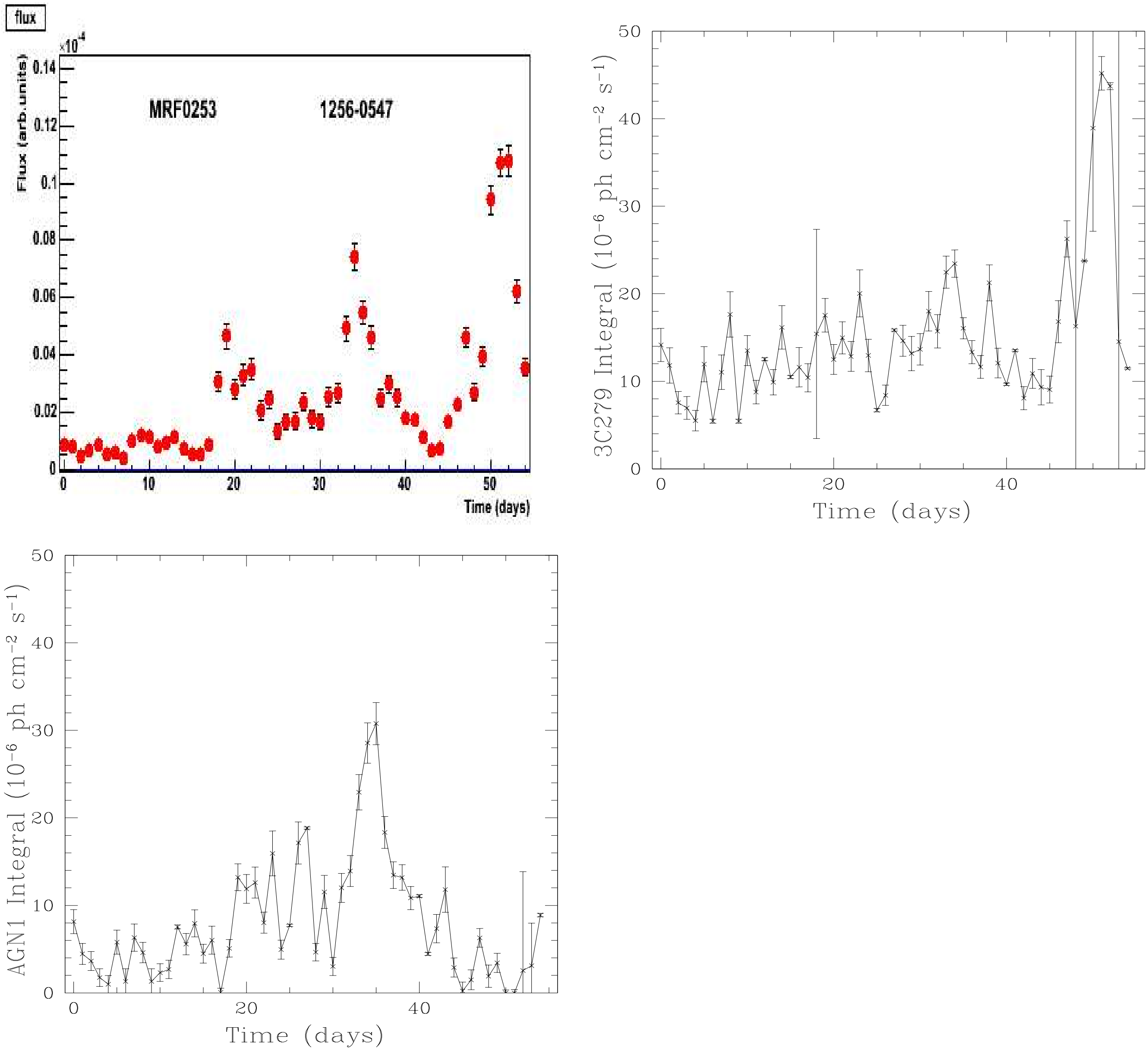

Fig. 16.— Top Left, a; Top Right, b; Bottom, c.